Digital Electronics.

Helpful Info.

MOSFET

Introduction

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- MOSFET (Metal-oxide semiconductor field-effect transistor) was fabricated for the first time in 1960.
- The MOSFET became the building block of VLSI circuits, however the applications of MOSFETs are not limited to VLSI circuits. They play an important role in power-electronics, and are becoming suitable for microwave applications.

MOSFET principles

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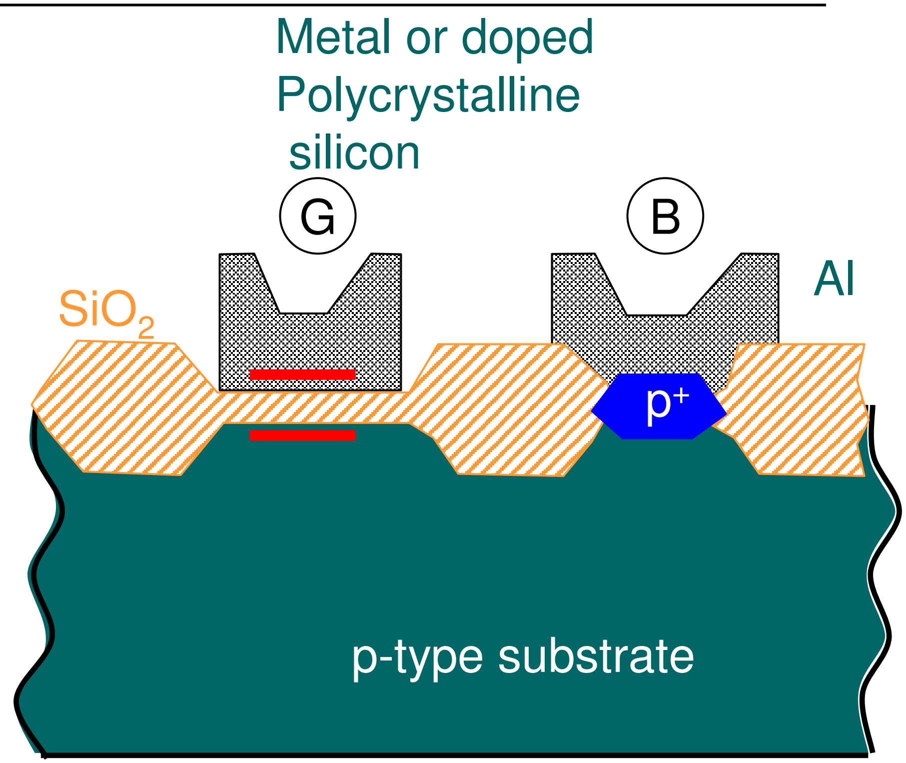
- MOSFET is developed from MOS capacitor
- The voltage applied to the gate of the MOS capacitor controls the state of the silicon surface underneath of SiO_2-Si.
- In this example, <u>negative</u> applied voltage attracts the holes from the p-type silicon to the surface (*accumulation*), while <u>positive</u> voltage above a threshold voltage attracts the electrons to the surface (*inversion*).
- These two states of the MOS can be used to make a voltage controlled switch.

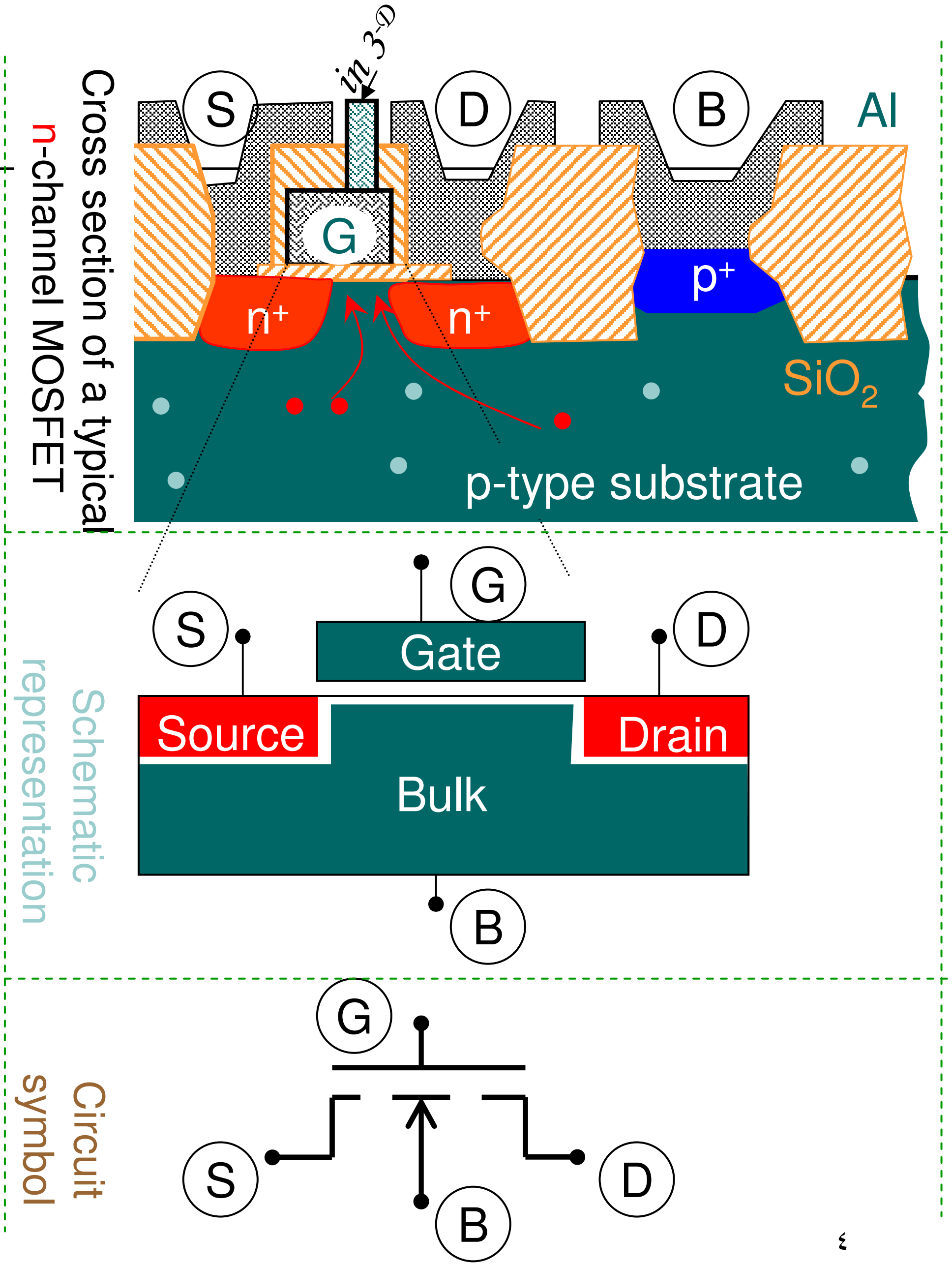


Cross section of MOS capacitor

MOSFET principles

To achieve this, the layer of the electrons on the surface is connected to the ends of n^+-layers (*source* and *drain*). The region between the layers is called *channel*)

- The existence of electrons in the channel corresponds to *ON* switch.
- When the gate voltage is below the threshold value, the electrons in the channel disappear and this corresponds to *OFF* state of the switch.
- The structure can be used as a voltage-controlled current source. *How*?



MOSFET principles

This is possible, because at higher drain-to-source voltages the current following from the source to the drain (ON state) does not increase linearly with the drain-to-source voltage but saturates. (will be soon explained)

- Very frequently, the bulk and the source are together connected to the common reference potential.
- The effect of the bulk-to-source voltage is called body effect (will be also soon explained).
- Last figure shows n-channel MOSFET, the same analogy can be applied to p-channel MOSFET.

MOSFET as a switch

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- The energy-band model helps in understanding the response of electrons and holes to the externally applied voltage.
- It should be noted that MOSFET effects must be considered in two dimensions:
  1. The first dimension is to express the gate voltage-related effects (x-direction)
  2. The second dimension is express the drain-to-source voltage- related effects (y-direction).
- Therefore, the energy-band should be plotted in two dimensions (x- and y-directions)

MOSFET as a switch

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- Switch ≡ *ON*↔*OFF* states.
- The gate voltage is determined by the potential at the surface of the silicon. This potential with respect to the bulk will be denoted as φ_s.
- It appears as a natural to take the zero potential as a reference point when different conditions of the silicon surface are considered (i.e. different gate voltages)
- The zero surface-potential is called *flat-band* condition. In this case, the electric-potential line, and hence the potential-energy lines are flat.
- The flat bands do not occur for zero gate voltage, due to the effects of work function difference and oxide charge
- The voltage needed to bring the silicon surface into flat-band conditions is called *flat-band* voltage.

MOSFET as a switch

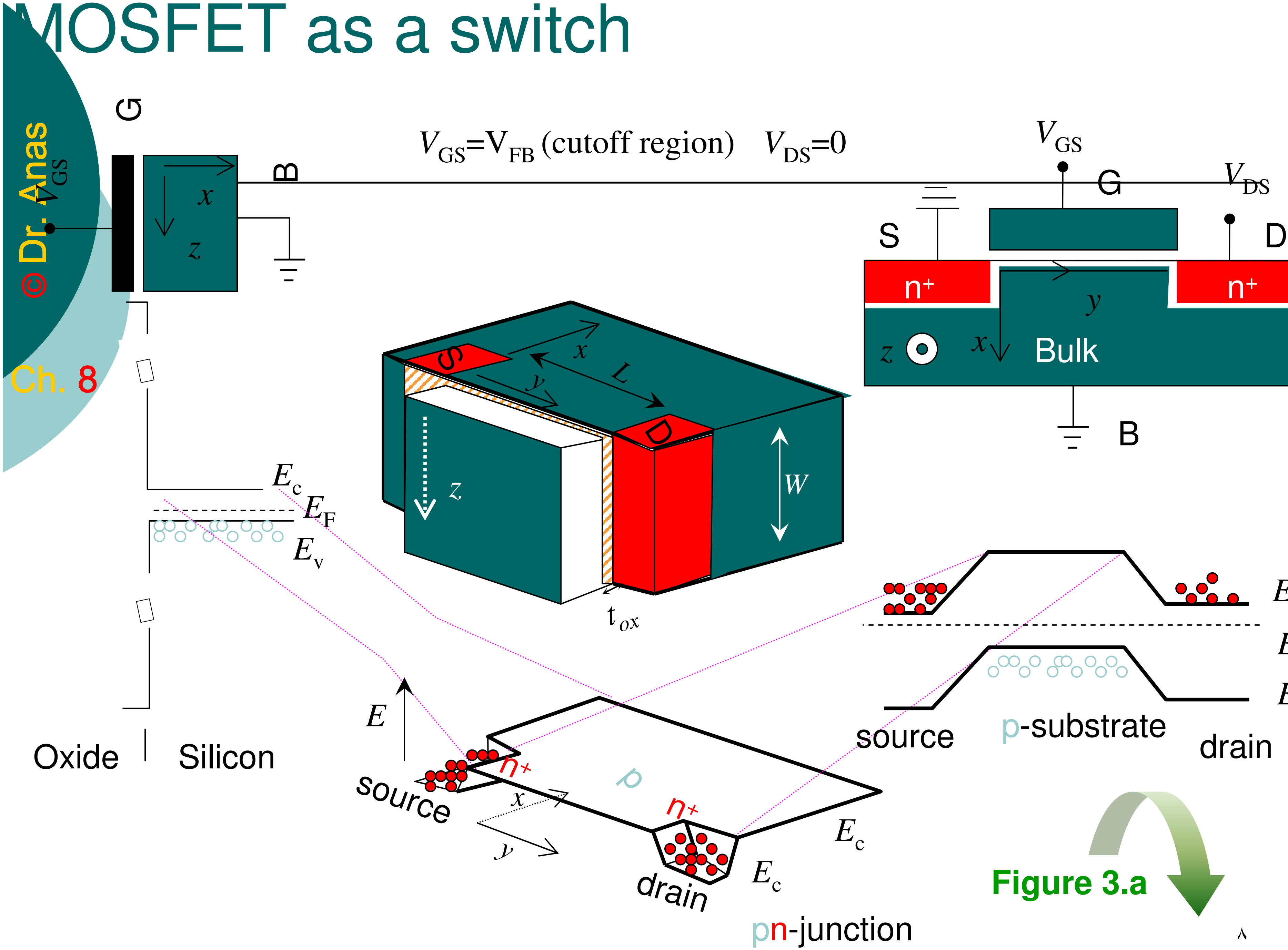

Figure 3.a

MOSFET as a switch

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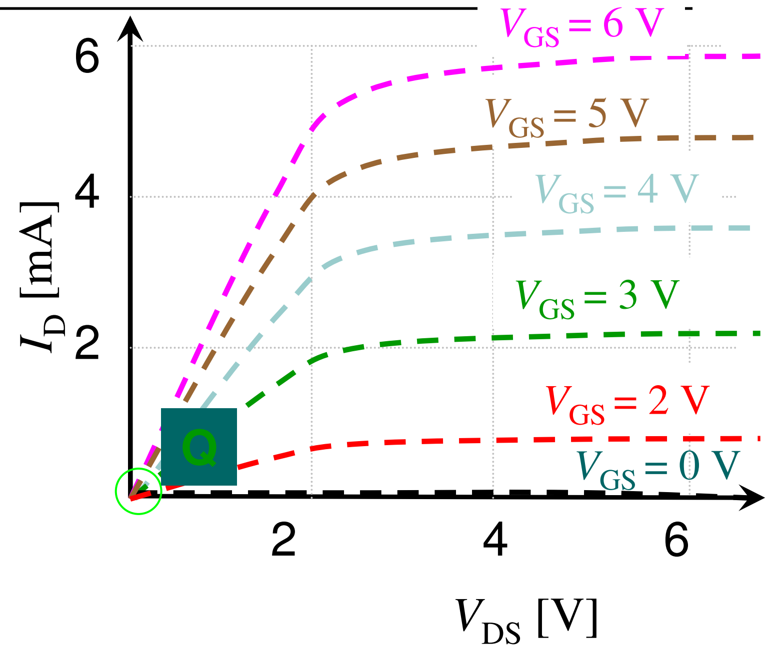
Figure 3.a illustrates the MOSFET in the *flat-band* condition. Note that the bulk and the source are short circuited and taken as a reference potential, and no drain-to-source voltage is applied (V_{DS}=0).

- Note, as long as there is an energy barrier between the drain and the source, applying a voltage between the drain and the source (V_{DS}) does not produce any electron current flow. The MOSFET is said to be in cutoff region.
- Figure 3.b, shows that the drain current is zero for any value of V_{DS} given that V_{GS}=0 ,



Transfer characteristic

Figure 3.b

MOSFET as a switch

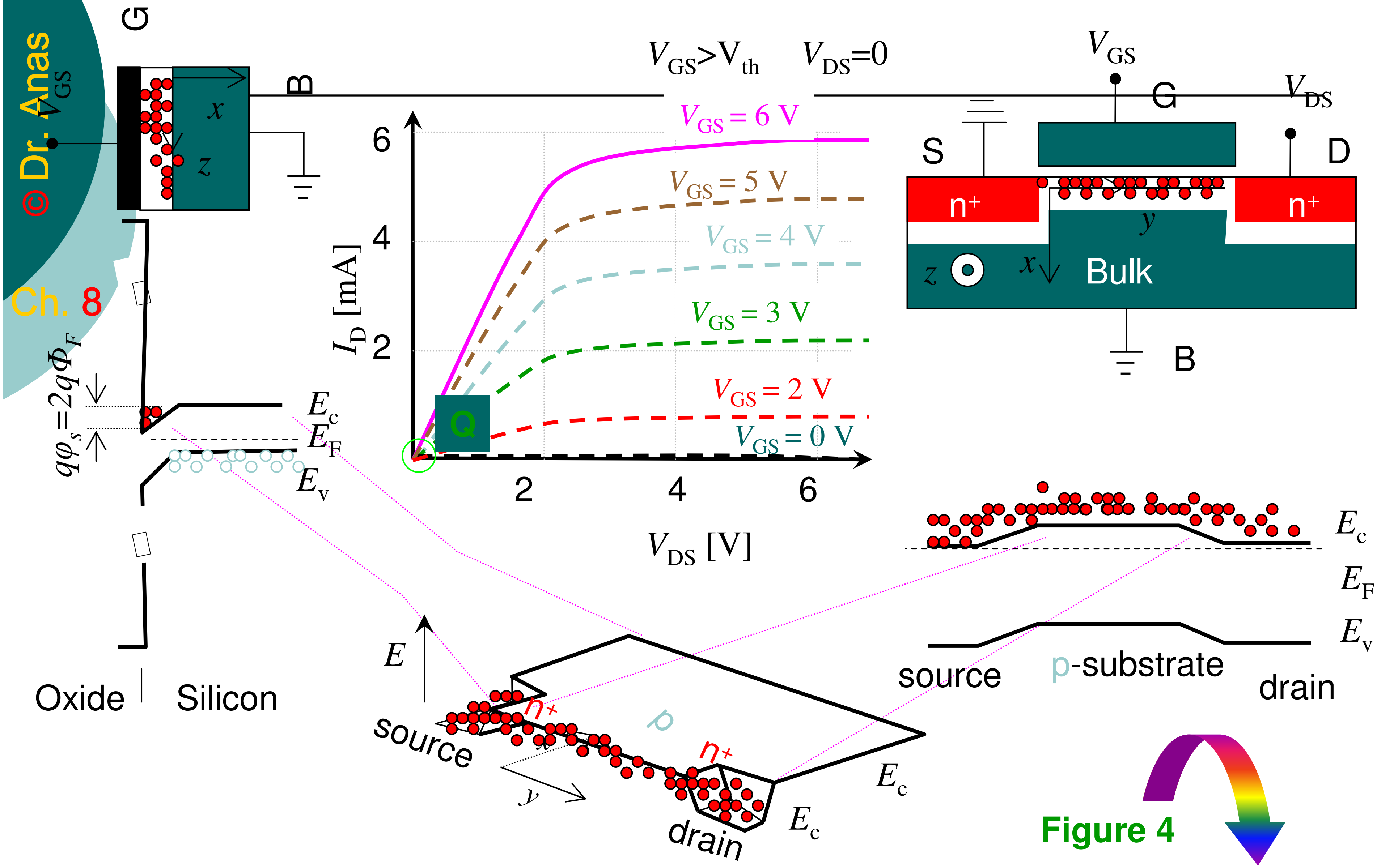


Figure 4

MOSFET as a switch

To set the MOSFET in *ON* mode, the energy-potential barrier between the source and the drain has to be reduced. This achieved by applying a positive gate voltage (with respect to the source) that is larger than a threshold voltage ($V_{GS}>V_{th}$).

A part of the voltage will drop across the oxide, the other part will appear as a surface potential φ_s. This positive surface potential bends the reference bulk potential downward, see Figure 4.

How much should the energy barrier be reduced before the electrons flow from the source to the drain?

- To answer this important question, let us consider the position of the Fermi level at the silicon surface. To have a significant concentration of electrons at the surface of the silicon, the Fermi level should be closer to the bottom of the CB than to the top of the VB. As the bands are bent at bottom of the CB moves toward the Fermi level while the top of the VB moves away from the Fermi level.
- Once the Fermi level is closer to the CB, the occupancy of electrons in the CB is larger than that of holes in the VB. At this stage, the inversion layer (channel of electrons) is being created.
- However the concentration of electrons is not significant before the surface potential reaches the value of $2\phi_F$ (strong inversion condition). Beyond this point, the bands almost saturates, see Figure 5.

MOSFET as a switch

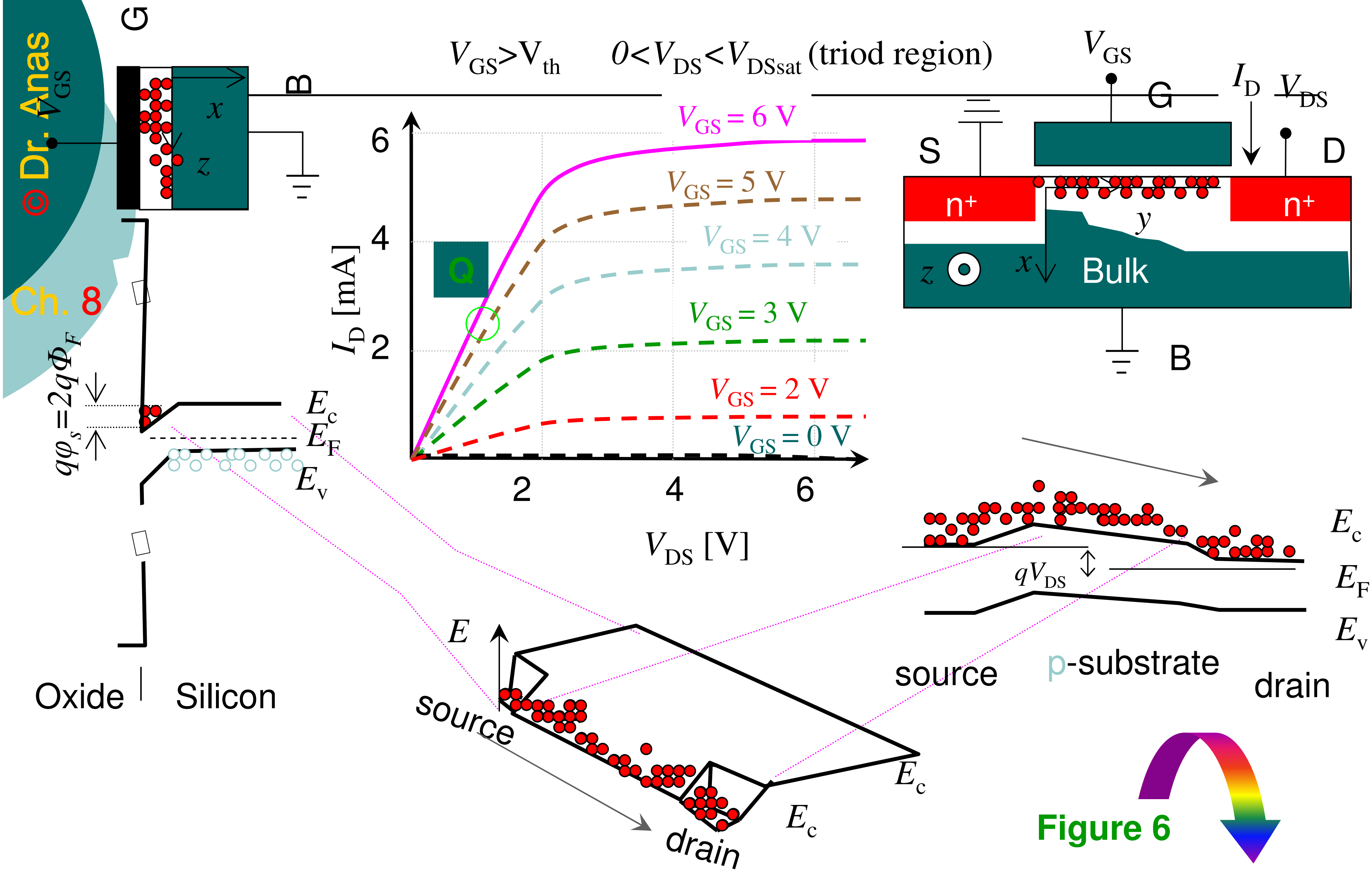


Figure 6

MOSFET as a switch

If the bottom of the CB of the drain is lowered with respect to the source, the electrons in the channel will start rolling down to the drain.

The lowering of the CB of the drain is achieved by applying a positive voltage to the drain with respect to the source, V_{DS}.

The two main factors influencing the value of the current I_D are:

1. The slope of the energy band ($\alpha\ V_{DS}$)
2. The concentration of electrons in the channel ($\alpha\ V_{GS}$-V_{th})

$$I_D = \beta(V_{GS} - V_{th})V_{DS}$$

- The pre-factor β depends on the capacitance of the oxide
- The last equation, predicts a linear dependence of the drain current on the drain-to-source voltage. This is correct for small values of V_{DS}. This region is referred as the *linear region*.
- *Why does saturation occur*? (we will see soon)

MOSFET as a voltage controlled current source

- When the MOSFET operates as a closed switch ($V_{GS}>0$, $0<V_{DS}<V_{DSsat}$), the normal electric field from the gate voltage V_{GS} holds the electrons in the inversion layer while the lateral electric field from the drain-to-source voltage V_{DS} rolls the electrons from the source to the drain. The resistance of the channel determines the slope of the linear I_D-V_{DS} characteristics.
- To use the MOSFET as a current source, I_D should become independent of V_{DS}. This happens at larger drain-to-source voltages ($V_{DS}<V_{DSsat}$), an effect referred as a current saturation.
- There are two different mechanisms that can cause drain current saturation in MOSFETs: (discussed soon)

MOSFET as a voltage controlled current source

As the drain-to-source voltage increased, the lateral electric field in the channel is increased as well, and may become a stronger than the vertical electric field due to the gate voltage. This would first happen at the drain end of the channel. In this situation, the vertical electric field is unable to keep the electrons at the drain end of the channel as the lateral field sweeps them into the drain. The channel is *pinched off* at the drain end. The drain-to-source voltage at which this happens is called the *saturation voltage* V_{DSsat}.

- Any increase of V_{DS} beyond V_{DSsat} expands the region into which the lateral field is stronger than the vertical field in the channel, effectively moving the pinch-off point closer to the source. The region created between the pinch-off voltage and the drain is basically a depletion region at reverse-biased drain-to-substrate junction. Note that we are considering the surface area of the junction, which is influenced by the gate field. Consequently, the surface region of the pn-junction is not reverse-biased until V_{DS} reaches V_{DSsat}. This is different from the bulk region of the junction, which is in reverse-bias for any positive V_{DS} voltage.

MOSFET as a voltage controlled current source

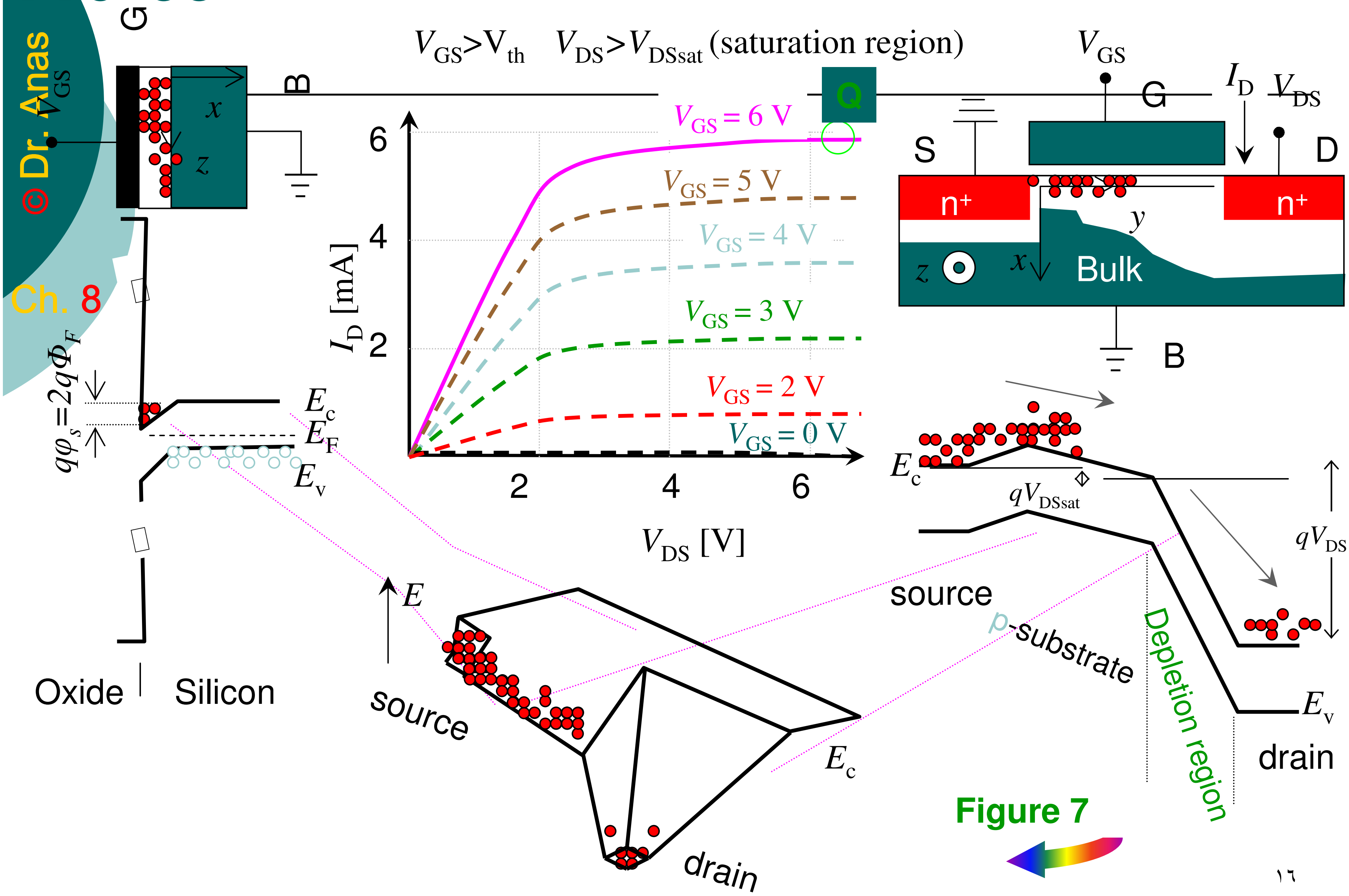


Figure 7

MOSFET as a voltage controlled current source

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The voltage drop across the surface depletion region is V_{DS}-V_{DSsat}, which is the voltage increase beyond V_{DSsat}. The remaining part of the drain-to-source voltage drops between the pinch-off point and the source. In this region, the vertical field is still stronger than the lateral field.

Figure 7 shows very steep energy bands in the depletion region, which represents the situation of a very strong lateral field in this region. Electrons do not spend much time on this very steep part of the bottom of the CB; they very quickly roll down into the drain. This part of the drain-to-source region offers little resistance to the electrons.

- Although an increase of V_{DS} beyond V_{DSsat} continues to lower the CB in drain, Figure 7 shows that this does not increase the drain current.
- The electrons in this shape of energy bands can be compared to a waterfall: the water current depends on the amount of water before the fall (the channel) and not on the height of the waterfall (V_{DS}-V_{DSsat}).
- It is obvious that the drain current depends on the gate voltage even in the saturation region, this is because the gate voltage determines the number of electrons in the inversion region. This useful property enables the current source to be controlled by the gate voltage, and the saturation current is different for different values of V_{GS}.

Types of MOSFETs

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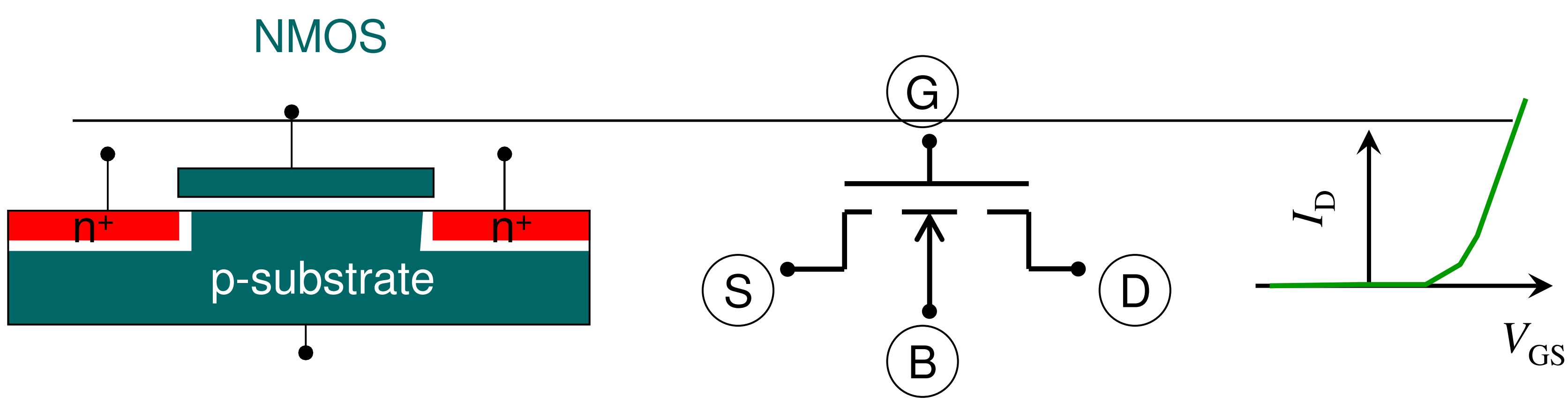
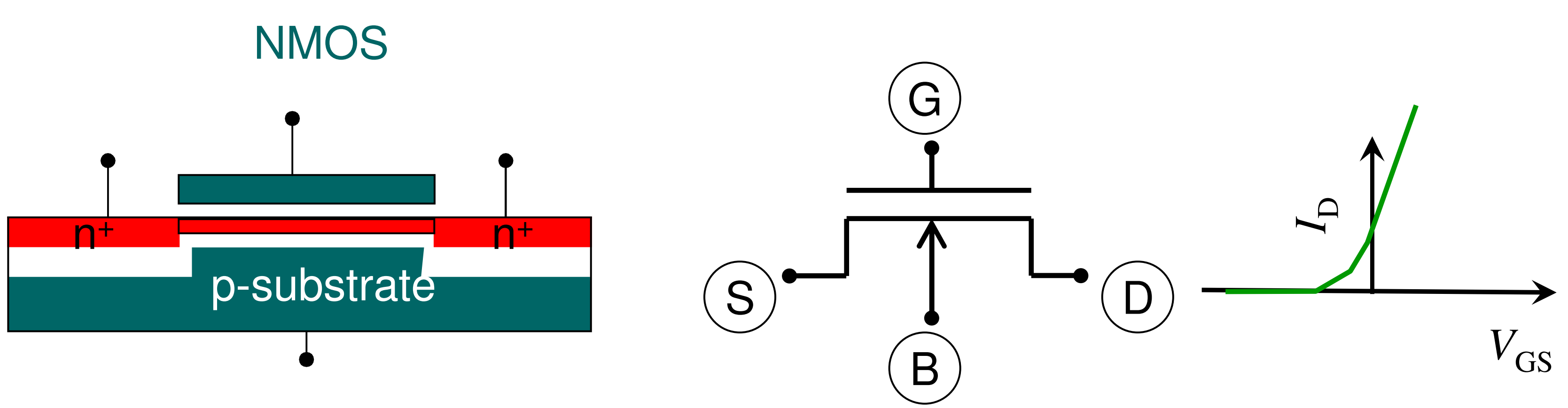
En... (normally OFF)



Depletion
(normally *ON*)



Types of MOSFETs